Groundwater Model Construction and Calibration for the Prolific Biscayne Aquifer - Problems and Unique Solutions

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ABSTRACT

The Biscayne aquifer is a shallow, but prolific aquifer due to its very high transmissivity. The City of North Miami Beach, Florida, in the process of expanding its wellfield, was required to model the drawdown impacts and the potential for saltwater intrusion. This paper addresses groundwater model construction and calibration, the problems encountered with aquifer performance testing of the Biscayne aquifer in the City, and the unique solution to determine aquifer parameters. Two 72-hour constant rate discharge tests

(5 wells at 5,500 gpm and 2 wells at 8,833 gpm) were performed several days apart. One observation well located 300 ft from the center of pumpage in the first test recorded less than 0.1 ft of drawdown. Results from the tests were complicated by tidal influences on the groundwater levels and impacts due to rainfall. Fortunately, a severe storm moved through the area during the middle of the first test, which had a much greater stress on the aquifer than the planned aquifer performance test. Approximately 8.5 inches of rainfall fell in the area in less than 2 days. This resulted in an almost immediate net water level change within the Biscayne aquifer of approximately 5.0 ft during this storm period. Using the observed change in water level throughout the study area and knowing the rainfall intensity, a groundwater flow model was calibrated to simulate the response to the observed storm in order to determine the aquifer parameters. Once calibrated to these conditions, the model was used to simulate potential future impacts for the proposed wellfield expansion.

INTRODUCTION

The City of North Miami Beach, Florida is in the process of expanding its wellfield to provide the City with an average water supply of 30 million gallons per day (MGD) and maximum daily demand of 45 MGD. Currently, the City provides approximately 17 MGD to its customers and purchases the remaining water supply from a regional supplier. In order to modify its existing water use permit issued through the South Florida Water Management District (SFWMD), the City was required to model the drawdown impacts and the potential for saltwater intrusion. Due to a lack of site specific and regional hydrogeologic parameters, this project included aquifer performance testing. A plan was developed to collect hydrogeologic data and to provide a more detailed analysis of the estimated impacts resulting from a proposed increase in pumpage from the North Miami Beach wellfield. The plan included staff gauge installation, surveying, step-drawdown and aquifer performance testing of wells within the wellfield, construction and calibration of a groundwater flow model based on field data, deep monitor well construction and water quality testing, and an analysis of lateral saline water intrusion using particle tracking. This paper presents the results of the data collection, aquifer testing, analyses, and additional groundwater flow modeling performed to address concerns of the SFWMD relative to the subject permit, and unique solutions utilized for model calibration.

CASE STUDY

Hydrogeologic Setting

In the study area, the area surrounding the City of North Miami Beach, the Biscayne aquifer of the surficial aquifer system is the only source of fresh ground water. This shallow aquifer is one of the most prolific aquifers ever tested by the USGS due to the highly permeable limestone and sand, which compose it. This aquifer is thickest in the Atlantic coastal areas

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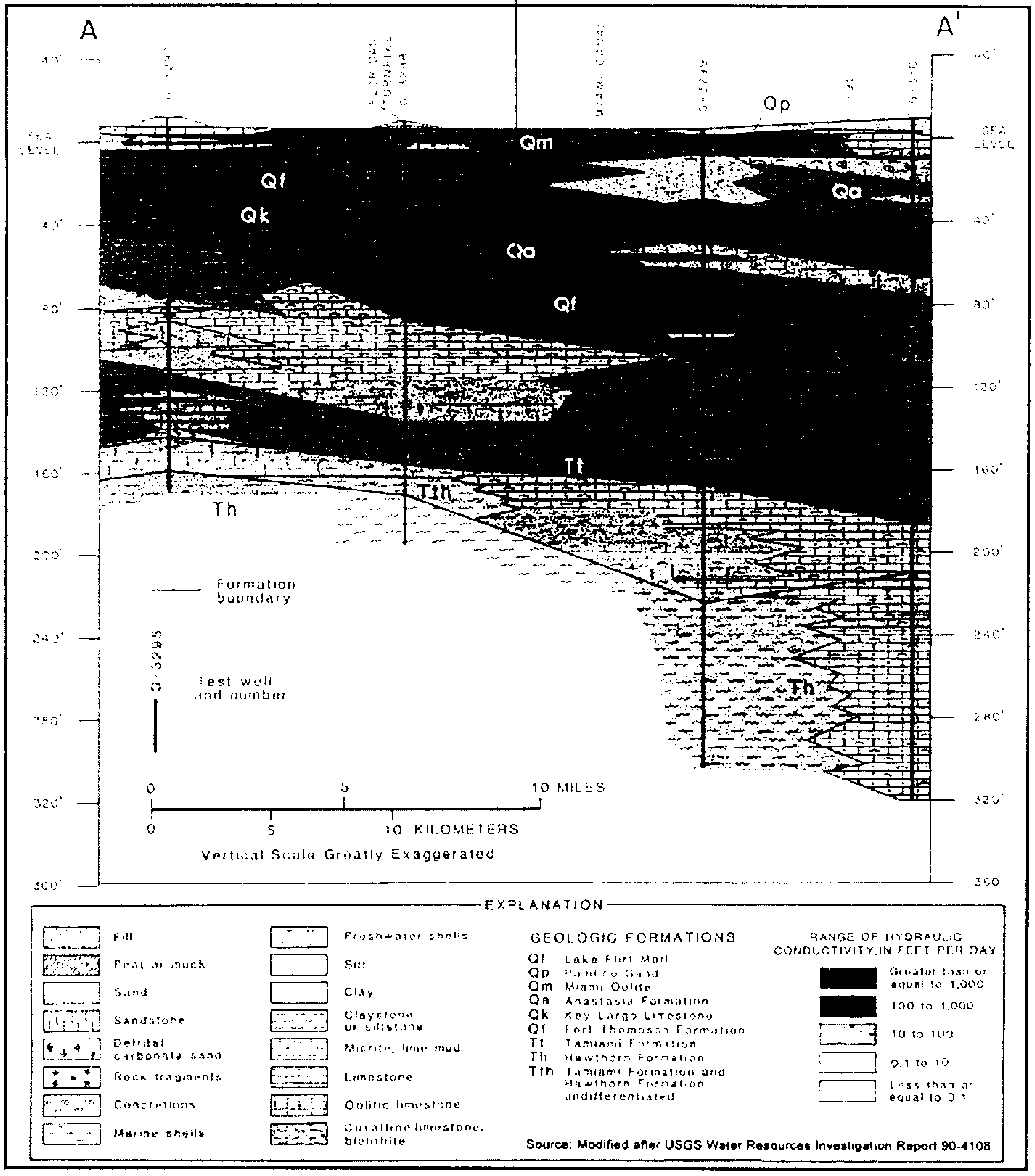

Source: Modified after USGS Water Resources Investigation Report 90-4108

Figure 1. Geologic cross-section for the southern end of study area.

Aquifer...

(Continued from page 29)

and pinches out in western Dade and Broward counties (Schroeder, 1958). In the study area the Biscayne is between 120 and 200 ft thick. Water table conditions prevail in this predominantly unconfined aquifer where variations in rainfall, evapotranspiration, drainage, and pumpage affect the resulting groundwater levels. The boundaries of the Biscayne aquifer are set by hydrologic properties of the sediments rather than formational contacts. The lowermost component of the Biscayne aquifer in the study area includes the limestone or shelly calcareous sandstone of the upper Tamiami formation. The remaining portion of the aquifer in this area from bottom to top includes the Fort Thompson formation, Key Largo limestone, Anastasia formation, Miami oolite, and Pamlico sand. The Fort Thompson formation consists of marls, limestone, and sandstones. The Key Largo limestone consists of coralline reef rock, ranging from hard and dense to soft and cavernous. The Anastasia formation consists of coquina, sand, calcareous sandstone, sandy limestone, and shelly marl. The Miami oolite is a massive to crossbedded oolitic limestone that contains vertical solution holes. Above the Miami oolite lie the Pamlico sand, which is a very fine to coarse quartz sand, and recent organic soils and marls. A relatively impermeable greenish marl of the Tamiami formation marks the base of the Biscayne aquifer (Schroeder, 1958). Figure 1 shows a geologic cross-section that runs through the southern portion of the study area, which was modified after one prepared by the USGS (Fish and Stewart, 1991).

The study area along with most of south Florida is greatly influenced by drainage canals. The drainage canal systems influence the hydrologic character of the study area not only by providing an effective means of managing stormwater runoff, but also by affecting the heads in the unconfined surficial aquifer system. The City of North Miami Beach predominantly lies between the C-8 and C-9 canals, which are controlled by the SFWMD. To better assess the influence the canal system has on the operation of the City's wellfield, the stage of the canal closest to the wellfield (C-9) was monitored during the aquifer performance testing.

Data Collection And Aquifer Performance Testing

A staff gauge was installed in the C-9 canal north of the water treatment plant site. This staff gauge was monitored along with select monitor wells and production wells during the aquifer performance testing. The elevations of the Department of Environmental Resource Management (DERM) monitor wells, the City's production and monitor wells that were accessible for water level monitoring, and the staff gauge installed in the C-9 canal north of the water treatment plant (WTP) were surveyed to verify measuring point elevations. The wells monitored during the aquifer performance testing included the City's production wells 1, 2, 4, 5, 8, and 11; the DERM monitor wells 1A, 1B, 2A, 2B, 4A, 4B, and 5A; and the SWIM wells 1 and 2.

Step-drawdown tests were performed on production wells 8, 11, and 12 to evaluate well efficiency and to determine specific capacity at various pump rates. Due to operational limitations of the production wells and the associated valving to control pump rates, the tests included two to four roughly half-hour steps with a declining pump rate for each successive step. In nearly all of the steps of the tests, the pumping water levels stabilized immediately and remained constant for the duration of the step. Analysis of the testing results showed that specific capacity ranges from 465 to 467 gpm/ft in well 8, from 862 to 2083 gpm/ft in well 11, and from 272 to 1030 gpm/ft in well 12. At maximum flow rates allowed by the pumps, well efficiencies were estimated using the Hantush-Bierschenk's method at 96 percent in well 8 at 1512 gpm, 13 percent in well 11 at 3750 gpm, and 2 percent in well 12 at 4330 gpm. The well efficiency estimated for well 8 is only based on two data points and is likely the least reliable. The actual aquifer drawdowns estimated for outside wells 11 and 12 when only these wells are pumping at the maximum pump rates listed above are 0.55 ft and 0.34 ft, respectively.

Two aquifer performance tests (APT) were included in the plan to obtain site-specific aquifer parameter data for model construction and calibration. Actually, three (3) aquifer performance tests were performed within the time period of September 28th and October 20th, 2000 as identified on Figure 2. Clusters of wells were pumped at constant rates while water levels in surrounding pumping and monitor wells were recorded using pressure transducers with data loggers or hand measurements. The first APT was run from October 1 to October 5, 2000 after several days of background data collection. The test included pumping production wells 1, 3, 8, 9, and 10 located at the WTP site at a total pumpage of approximately 5,500 gpm. Approximately two hours after starting the planned 72-hour test, a storm front began moving through the area that produced 8.53 inches of rain, based on data collected at the WTP rain gauge. Data collected at the SFWMD rainfall stations within or just outside the model area recorded between 11 to 15.5 inches of rain during the same time period.

The potentiometric surface of the Biscayne aquifer responded to this rainfall event by rising nearly 5 feet. The impact of the rainfall

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Figure 2. Hydrograph of one monitor well (Well 5) with rainfall during aquifer performance testing.

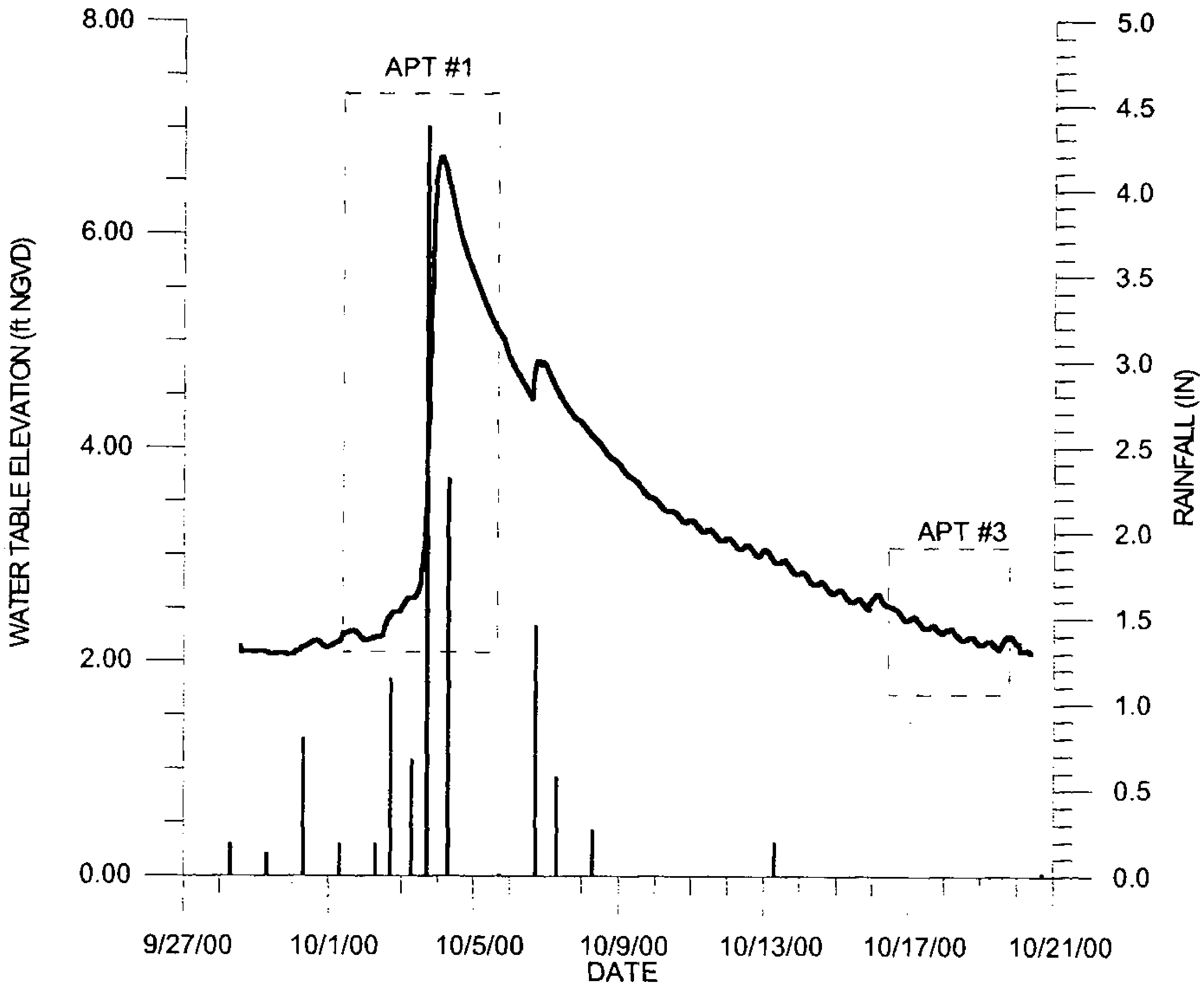


Figure 2. Hydrograph of one monitor well (Well 5) with rainfall during aquifer performance testing.

Aquifer...

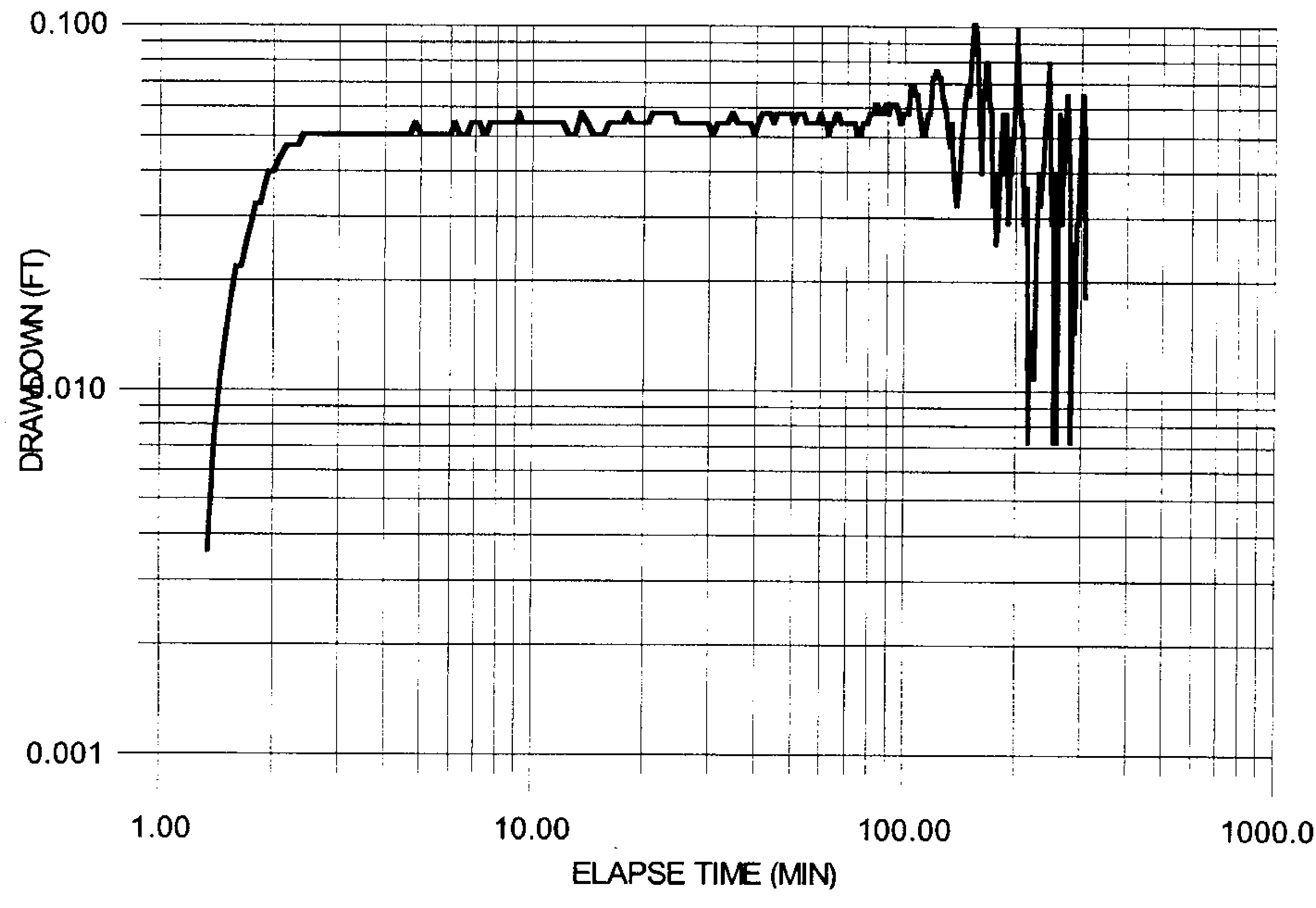
(Continued from page 30)

event completely overshadowed the minute drawdowns recorded prior to the beginning of the rain. The drawdown curves in Figure 3 shows that the initial drawdown recorded in monitor well 5A was approximately 0.06 feet prior to influences from diurnal variations and rainfall. This well is estimated to be approximately 300 feet from the center of pumpage for this pump test. The initial drawdown in SWIM 1 located approximately 270 feet from the center of pumpage was 0.03 feet prior to influences from diurnal variations and rainfall. However, SWIM 1 is completed into a lower portion of the Biscayne aquifer then monitor well 5A, which explains why drawdown impacts are less then observed in monitor well 5A. It appears as though water levels stabilize both in monitor well 5A and SWIM 1 about 10 minutes into the constant-rate discharge test. The Hantush-Jacob method was used to estimate hydrogeologic parameters. Although the time-drawdown curves did not match well to the Walton type curves, the method calculations resulted in average transmissivity, storage, and leakance values of approximately 3,737,000 gpd/ft, 0.05, and 26 day-1, respectively.

The second test was run from October 5 to 6, 2000 and included wells 11 and 12, pumping at about 8,900 gpm. The test was stopped early because the overall decline in the water table elevation, due to the continued recession of water levels after the huge rainfall event, overshadowed any measured drawdown from the constant-rate discharge test. The third test was run from October 16 to 19, 2000 and also included wells 11 and 12, pumping at approximately 8,833 gpm. Overall water table decline was observed during this test as well in addition to the diurnal variations, albeit at a smaller rate of decline. The initial drawdown observed in production well 5 during this third APT stabilized after 25 minutes of pumpage and is approximately 0.015 feet. Using the Hantush-Jacob method again, aquifer parameters were calculated for the area between well 5 and the center of pumpage between wells 11 and 12. The method calculations resulted in a transmissivity value of 16,871,030 gpd/ft, a storage value of 0.05, and a leakance value of 10 day-1. The geometric means of the hydrogeologic parameters were then calculated and used as the starting parameters for calibration of the groundwater flow model. The geometric mean values of transmissivity, storage and leakance were approximately 6,000,000 gpd/ft, 0.04, and 18 day-1, respectively.

Groundwater Flow Model

In order to determine the groundwater withdrawal impacts of the Biscayne aquifer system resulting from an increase in groundwater withdrawal, a numerical groundwater flow model was constructed using Visual MODFLOW. The model was used to simulate drawdowns in the Biscayne aquifer associated with the current allocated and proposed groundwater withdrawals. A three-layer model was developed to represent the layers of the Biscayne aquifer and lower surficial aquifer. The first layer (land surface to -30 ft NGVD) represents the upper Biscayne aquifer, the second layer (70 to 87 feet thick) represents the production zone, and the third layer (70 to 73 feet thick) represents a lower surficial aquifer below the production zone. The physical area of the model was divided into 193 rows and 198 columns with cell widths that vary from 1,000-foot squares at the model boundaries to 100-foot squares in the wellfield area. The canals were modeled as river cells with elevations varied using historic canal level data. The Biscayne Bay and the Atlantic Ocean in the model area were simulated using constant head cells in the first layer with tidal stages as head elevations.



Recharge to the Biscayne aquifer was simulated using the recharge package. Recharge in the calibration simulation was varied daily based on recorded rainfall and one hundred percent of the rainfall was used.

Normal (30-year record) rainfall data were used as collected at the Hialeah NOAA weather station in order to simulate rainfall for predictive simulations. The normal rainfall at the Hialeah station was 63.01 inches/year. Eighty percent of this precipitation was actually applied to the model, allowing twenty percent for runoff and initial evaporation prior to aquifer recharge. Evapotranspiration (ET) was simulated using the ET package. ET values were calculated using the Hialeah station normal temperature data and the Thornthwaite equation. The estimated annual total maximum ET rate of 53.97 inches was used in the steady state and predictive simulations. Monthly ET rates (September and October) were used in the calibration simulation.

To obtain a starting water level for the calibration simulation, a steady-state model simulation was run that included average annual rainfall and ET, average historic canal elevations, and estimated aquifer parameters. The resulting heads from this run were used as starting heads for the transient calibration simulation. Since the rainfall events showed a far greater influence on the groundwater levels than the pumping, it was determined that the rainfall events were more significant hydrologic events and would be better to calibrate the model to the rainfall events instead of the less significant aquifer performance tests. The aquifer parameters were then adjusted until simulated water levels approximated recorded water levels observed during the same time period. A comparison of observed versus simulated heads at nine observation points at three different times during the testing period is presented in Table 1 for model verification. Note that the dates include conditions before, during, and after the significant hydrologic event. The simulated heads match fairly well at all the observation points on all three dates chosen, which indicated that the model is calibrated.

(Continued on page 32)

Aquifer...

(Continued from page 31)

Table 1. Calibration wells with observed versus simulated water levels for three dates before, during and after the significant rainfall event.

	10/01/2000		10/04/2000		10/19/2000	
Well	**Observed**	**Simulated**	**Observed**	**Simulated**	**Observed**	**Simulated**
1A	2.33	2.19	5.82	6.02	2.24	2.37
1B	2.50		5.83		2.24	
2A	2.19	2.14	5.65	5.78	2.15	2.05
2B	2.39		5.74		2.16	
4A	2.33	2.27	5.92	6.02	2.28	2.08
4B	2.41		5.93		2.30	
5A	1.94	2.08	6.03	5.97	2.04	2.03
SWIM1	2.12	2.12	5.76	6.00	2.30	2.04
SWIM2	2.46	2.65	6.63	6.64	2.57	2.08

Due to the single parameter approach for the calibration of the model, the SFWMD requested that an attempt be made to incorporate the variability of the lithology and corresponding transmissivity across the model area. However, extensive hydrogeologic parameter and lithologic data were not available. In order to satisfy the request for the model to reflect the heterogeneous nature of the area as shown in Figure 1, parameter variability was added to the model using data from some regional models previously constructed for the area by the SFWMD, which showed variability across the region. Revisions to the hydrogeologic parameter data gathered from existing models included refinement of transmissivity, specific storage, and distribution of rainfall. Five regional USGS monitor wells were also added to the list of calibration wells to calibrate the model over a greater region. Data from a total of sixteen (16) observation wells were used to calibrate the model. The resulting hydrologic parameters from the calibration simulation are presented in Table 2.

Table 2. Calibrated hydrogeologic parameters.

Model Layer	Transmissivity (gpd/ft)	K_h (ft/day)	K_v (ft/day)	Specific Yield	Specific Storage
1	400,000	1358	21	0.115 to 0.23	0.003 to 0.006
2	1E6 to 50E6	1573 to 78,641	1100	---	1.2E-6
3	10,000 to 0.9E6	190 to 1720	172	---	1.4E-6

The objective during the calibration process was to match both the observed peaking of water levels at various observation locations and the recession of the water once the major storm passed the City. The peaking of the water levels in the model is influenced greatly by the specific yield of layer one, the magnitude of recharge value, and the horizontal hydraulic conductivity (Kh). The vertical hydraulic conductivity (Kv) had a smaller effect on the peaking of simulated water levels as long as the values were high. The horizontal hydraulic conductivity, the heads in the river cells (drainage canals) and the heads in the constant head cells (Biscayne Bay and Atlantic Ocean) predominantly controlled the recession of the water levels simulated in the model. Unfortunately, there is not an elegant way to distribute rainfall on a daily basis from six different stations within Visual MODFLOW except through zoning, which is extremely cumbersome. Therefore, the translation of the recharge package in Visual MODFLOW was turned off for the transient calibration simulations so that a detailed interpolated distribution of rainfall could be constructed for each day or fraction of a day rainfall occurred and a recharge package could be assembled outside of the preprocessor.

The statistics for the final calibrated model are as follows. The mean error for 704 data points is 0.18 ft. The mean absolute error is 0.40 ft, and the standard error of the estimate or the calibration residual is 0.02 ft. The root mean squared error is 0.67 ft, and the normalized root mean squared error is 6.97%. Due to the favorable calibration statistics and the well-matched hydrographs with appropriate peaks and recession curves, the authors consider this model as being well calibrated.

In order to predict the impacts to surrounding water users several predictive simulations were run. MODPATH was also used to predict the movement of particles from the brackish water interface toward the wellfield. A line of particles was inserted into both layer one (the upper Biscayne aquifer) and layer two (the production of the Biscayne aquifer). The location of the line of particles was inserted approximately along the saline water interface as defined by the USGS (Sonenshein, 1997) as shown in Figure 4. The model results showed that none of the particles flow toward the wellfield.

The SFWMD would only be satisfied that the withdrawals are permittable and would not cause harm, if there was no significant net movement of water across the interface. The average daily withdrawal of 30 MGD was used in a steady-state simulation with normal rainfall and ET. Existing permitted legal users of the water supply were included in this and subsequent runs. This simulation also showed that the requested water allocation would not have significant impacts on existing legal users or on movement of the brackish water interface. Next, the maximum daily flow of 45 MGD was simulated with the existing and proposed wells in a 90-day no recharge run. This simulation again showed no significant impacts to surrounding users and no movement at the interface due to the very high transmissivity of the Biscayne aquifer in the area. This simulation likely represents the worst-case scenario that could occur within the City. Even though the maximum daily flow would actually only occur at most a few days a year, the results of the 90-day no recharge were favorable.

Another simulation requested by the SFWMD was one that would include one-year transient simulation with 1-in-10 year return drought conditions. For this simulation the average daily flow of 30 MGD was used since it is the water supply demand required over a longer period of time. The 1-in-10 year return drought condition for this area was calculated to between 46 and 48 in/yr of rainfall. The period of time chosen by the SFWMD as being representative of the 1-in-10 year drought for this area was from May 1989 through April 1990. The average of the data from the nearest rainfall stations for this time period equaled 48.88 in/yr. In order to be more conservative with the estimation of potential impacts, a 30-MGD one-year transient simulation was run with only 32 in of rainfall for the year, which represented approximately a 1-in-100 year drought condition. The resulting drawdown from that run is presented in Figure 4. The 0.25 ft drawdown contour extends approximately 2 miles from the center of pumpage. The maximum drawdown simulated was about 1.5 ft.

(Continued on page 35)

Aquifer...

(Continued from page 32)

CONCLUSIONS AND RECOMMENDATIONS

Significant hydrologic events are often used to calibrate groundwater flow models, such as single pump tests; long-term modification of pumping rates from whole wellfields; and climatic events such as wet seasons, droughts and storm events. When aquifer transmissivities are very high, significant hydrologic events such as storm events may provide the only significant and measurable impact to potentiometric surface elevations that allows for the regional estimation of aquifer parameters through model calibration. Problems encountered in the case study included the different data collection methods and times of both rainfall and water elevations. These included daily rainfall measurement instead of continuous or hourly measurement and only maximum daily recorded water levels for the USGS monitor wells included in the model calibration. When one has a highly responsive aquifer sensitive to recharge events, the simulated timing of the rainfall events in the constructed model can have a large influence on the calibration of observed water levels that are measured with continuous data loggers. The authors therefore recommend everyone performing aquifer performance tests and long-term monitoring should collect as much rainfall and water level data that can be collected. A modeler considering the complexities of the hydrologic system and groundwater flow model can then determine the degree to which one uses the available time-dependent data. Often aquifer performance tests are planned for periods of no anticipated rainfall events, as were the case studies' APTs. This concept should be reconsidered for certain hydrogeologic and hydrologic conditions as presented here.

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